Effective Health Diagnosis System for Underground Pipeline Networks Using Distributed Fiber Optic Sensing

YANG Wen-Tao & ZHANG Tian-Yu & FENG Wei-Qiang*
Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, China

YANG Wen-Tao
Anchor Monitoring Technology (HK) Limited, Hong Kong

Ngai Kwok-Leung, Cheung Hoi-Yan
Electrical and Mechanical Services Department of HKSAR

Ng Wan-Lung Sean, Chan Chi-Ho Philip
Ove Arup Partners (HK) Limited

*Corresponding Author

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ABSTRACT

The safety of urban underground pipeline networks is identified as a critical factor for maintaining urban resilience and public safety. In this study, an integrated health diagnosis system based on Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) is demonstrated for the real-time detection of pipeline leakages. Laboratory experiments were performed to characterize the acoustic and thermal responses under various leakage intensities and fluid temperatures. It is observed that the DAS system provides an immediate vibration-based response, with the vibration power spectral density (PSD) increasing from -50 dB to -20 dB upon the occurrence of a leak. This high-frequency spectral footprint, specifically identified in the 1.4 to 1.5 kHz range, allows for millisecond-level early warning and precise spatial localization. Concurrently, the DTS system provides thermal verification, showing a gradual temperature change with a detection delay of approximately 14 minutes in the tested insulation pipe. While DTS exhibits a temporal lag due to fluid seepage and heat conduction through the insulation layer, it remains significantly less susceptible to environmental noise, serving as a decisive criterion for event verification. The synergy between the high timeliness of DAS and the high confidence of DTS effectively resolves the trade-off between monitoring speed and accuracy, providing a robust technical solution for the proactive safety management of urban subsurface infrastructure. Looking forward, the integration of this dual-sensing optical framework with Internet of Things (IoT) devices holds great potential to establish a comprehensive, multi-parameter monitoring network, enabling an advanced analysis of both structural deformations and leakage events.

Keywords: Distributed Acoustic Sensing (DAS); Distributed Temperature Sensing (DTS); Pipeline leakage monitoring

1 INTRODUCTION

Urban underground pipeline networks, encompassing water supply, drainage, gas, heating, and industrial conduits, constitute the critical infrastructure essential for maintaining modern urban functions. With the continuous advancement of urbanization and the implementation of resilient city strategies, the scale and density of these networks have expanded significantly (Hoekstra et al. 2018; Zhu & Chang 2020; Sharma et al. 2021). Under the dual influence of complex corrosive environments and prolonged lack of systematic maintenance, structural defects such as internal rust, leakage, and pressure imbalances have become increasingly prominent (Tan & Long 2021; Hu et al. 2024; Li et al. 2025). The occurrence of pipeline leakage is identified as a primary induction factor for urban geological hazards, accounting for approximately 60% to 70% of ground collapse accidents (Wang & Xu 2022; Wang et al. 2022). The evolution of geological disasters induced by pipeline failures typically follows a chain-like process (Augarde et al. 2003; Shiau et al. 2021; Dai et al. 2024; Park et

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al. 2024). This process is generally initiated by pipe defects and subsequent leakage, followed by high-velocity fluid injection, internal erosion of surrounding soils, the formation of underground cavities, and ultimately, the loss of surface structural stability. These cavities are often undetectable from the surface due to the arching effect of road structures, but once the dimensions exceed a critical threshold, instantaneous ground collapse is triggered (Li et al. 2023; Wang et al. 2023; Dai et al. 2024). Therefore, the precision sensing and real-time monitoring of leakage events are essential for mitigating the operational risks of urban geological hazards. Conventional monitoring technologies still have significant technical bottlenecks and application limitations. Ground Penetrating Radar (GPR) is primarily restricted to periodic inspections due to its reliance on manual operation and susceptibility to interference (Tong et al. 2020; Klewe et al. 2021). Similarly, traditional acoustic methods are constrained by rapid signal attenuation, limiting their effective coverage (Singh et al. 2021). Furthermore, traditional approaches often fail to provide continuous and long-range monitoring capabilities.

Given this limitation, the emergence of Distributed Fiber Optic Sensing (DFOS) provides a robust alternative for real-time health monitoring. Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) offer continuous sensing capabilities over tens of kilometers with high spatial and temporal resolution (Barrias et al. 2016; Schenato 2017; Lu et al. 2019; Ashry et al. 2022). Concurrently, the Raman-based DTS system demodulates absolute temperature profiles by analyzing the intensity ratio between anti-Stokes and Stokes components (Dakin et al. 1985). Recent research has witnessed a transition in DTS applications from passive sensing toward active heating methods (ADTS) and ultra-high-resolution differential sensing (DdTS) to overcome sensitivity bottlenecks in identifying micro-leakages (Li et al. 2023). Concurrently, DAS systems, operating on the principle of phase-sensitive optical time-domain reflectometry (φ-OTDR), function as a continuous array of virtual sensors to quantify dynamic vibration signals (He & Liu 2021). The evolution of DAS technology has shifted from basic temporal-frequency analysis toward intelligent feature recognition powered by deep learning architectures, such as Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks, to enhance signal-to-noise ratios in high-noise environments (Zhang et al. 2023; Huang et al. 2024; Lang & Wang 2024).

Despite these advancements, several critical challenges persist in the engineering application of DFOS for pipeline safety. While these technologies are effective for qualitative leak identification, the high false alarm rate induced by complex urban environmental noise remains a significant operational burden (Zuo et al. 2020; Li et al. 2025). Furthermore, current monitoring schemes often lack the capability for the deep decoupling of multi-modal data, and a robust quantitative relationship between leakage intensity and multi-dimensional fiber optic signals has yet to be fully established (Xia et al. 2023). Additionally, the supporting foundation of underground pipelines is highly susceptible to differential settlement, horizontal displacement, or tilting driven by complex hydrogeological conditions. These structural deformations are often the underlying causes of stress concentration and eventual pipeline rupture (Hachiya et al. 2022; Zhang et al. 2024). This gap hinders the transition from simple event detection to precise, real-time quantitative assessment of pipeline health. Therefore, further investigation into the response characteristics of acoustic frequency bands and thermal gradients under varying leakage conditions is required to enhance the reliability and precision of integrated monitoring systems.

In this study, a comprehensive monitoring methodology for underground pipeline leakage is proposed based on the synergistic integration of DAS and DTS technology. The investigation is focused on characterizing the acoustic frequency band variations and temperature field responses under various leakage intensities and fluid temperatures. By analyzing the vibration signatures and thermal anomalies associated with escaping fluids, the sensing performance and localization accuracy of the integrated fiber optic system are rigorously evaluated. Laboratory experiments were performed to validate the effectiveness of these sensing techniques in capturing transient leakage events and identifying steady-state thermal gradients. It is demonstrated that the fusion of high-frequency vibration data and stable temperature profiles provides a reliable means for the timely detection of pipeline failures, effectively addressing the technical trade-offs between response time and measurement accuracy. This approach offers a significant technical basis for the proactive safety management of urban subsurface infrastructure and lays a crucial foundation for future synergistic integration with multi-dimensional IoT sensors.

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2 METHODOLOGY AND PRINCIPLES

2.1 Distributed Temperature Sensing (DTS) Based on Raman Scattering

The implementation of DTS as a thermal monitoring tool leverages the sensing fiber as a continuous linear array, with its operational principle fundamentally rooted in the Raman scattering effect. This phenomenon is characterized by the inelastic scattering occurring between incident laser photons and optical phonons within the silica fiber core (Dakin et al. 1985; Ren et al. 2018; Zuo et al. 2020). The backscattered light is characterized by two distinct components, the Stokes and anti-Stokes lines. The intensity of the anti-Stokes component is observed to be highly sensitive to environmental temperature fluctuations, whereas the Stokes component remains relatively stable. By calculating the power ratio between these two components and applying time-of-flight analysis, absolute temperature profiles along the pipeline are demodulated. The DTS equipment used in this study is capable of identifying temperature anomalies with ±0.5 °C accuracy and 1 m spatial resolution.

In the context of pipeline leakage monitoring, Raman scattering is independent of the fiber strain state, thereby ensuring that thermal anomalies induced by leaking fluids are captured without interference from structural deformations or ground movements. This decoupling capability renders Raman-based DTS a more reliable choice for identifying localized cooling or heating effects associated with subsurface pipe leakages.

2.2 Distributed Acoustic Sensing (DAS) Based on Rayleigh Backscattering

DAS system based on Phase-Sensitive Optical Time-Domain Reflectometry (φ-OTDR) is implemented as the high-frequency vibration monitoring (Lu et al. 2010; He & Liu 2021; Wang et al. 2022). The sensing process is initiated by launching highly coherent laser pulses into a single-mode sensing fiber, where Rayleigh backscattering is induced by sub-wavelength refractive index inhomogeneities. These scattering centers form a stationary interference pattern along the fiber length. When acoustic waves or mechanical vibrations generated by fluid leakage impinge upon the fiber, dynamic axial strain is induced, which modifies the local optical path length through the photo-elastic effect. Unlike direct detection methods, the φ-OTDR system utilizes coherent detection schemes to demodulate the linear optical phase shift of the backscattered signal. This allows for the quantitative reconstruction of the amplitude, frequency, and precise spatial location of the acoustic field.

The DAS system operates with a broad bandwidth, enabling the capture of high-frequency jetting noises produced by high-pressure leakages. Because the sensing signals are acquired independently for each spatial interval, disturbances are not accumulated over distance, allowing for high-sensitivity vibration monitoring over ranges exceeding 40 km. The DAS equipment used in this study can offer a frequency response ranging from 0.1 Hz to 50 kHz and a spatial resolution of 1 m.

The integration of DAS-derived vibration signatures with DTS-derived thermal gradients establishes a multi-dimensional data framework for the identification of pipeline failures under varying operational intensities.

3 INDOOR PIPE LEAKAGE SYSTEM DESIGN AND TEST PROGRAM

A simulated monitoring system for urban water supply pipeline leakage was constructed in a laboratory setting to evaluate the feasibility of DAS technology. The physical model and the corresponding sensor layout are presented in Figure 1. This experimental platform utilizes a prefabricated direct-buried insulation pipe structure. This structure consists of an internal stainless steel working pipe, a middle layer made of rigid polyurethane foam for insulation, and an external anti-corrosion sheath composed of high-density polyethylene. To facilitate distributed monitoring, multiple sensing conduits are embedded within the insulation layer near the stainless-steel pipe to house the optical sensing fibers. A controllable valve is also installed on the pipeline section to simulate leakage events with different aperture sizes. The fluid environment is managed by connecting the pipeline ends with flexible hoses to a water pump, which creates a closed loop with adjustable water pressure. Furthermore, a heater is integrated into the system to increase the temperature of the circulating water, allowing for the simulation of various leakage scenarios. Optical sensing cables are installed both inside the conduits of the insulation pipe and along the exterior of the copper pipeline. Real-time vibration responses and temperature changes are monitored using a BL-DAS equipment from Brillnova and a FET8609D DTS equipment from PREMIER during both normal operation and leakage conditions.

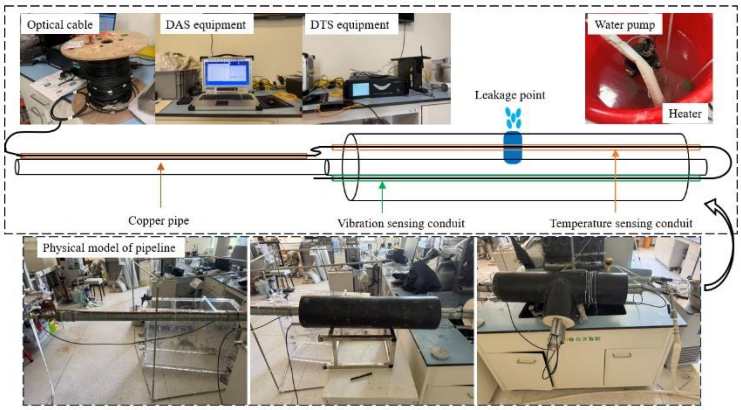


Figure 1: Schematic diagram of the pipeline model test system

Multiple controlled experiments were conducted on this platform to collect high-fidelity vibration signals under four typical states: static, normal operation, leakage, and noise interference (as shown in Table 1). The primary objective is to identify the relationship between the water flow state and changes in the vibration spectrum by comparing the frequency characteristics of these signals. Therefore, various experiments were performed to obtain steady-state vibration data under different conditions. The experimental procedure focuses on responses to transient events and system calibration. Initially, tapping was performed at a fixed point on the water supply pipeline between 19:46 and 19:50 while the water was either stationary or moving at a low speed. This action generated a wideband transient vibration source at a specific time and location to calibrate the spatial positioning and response accuracy of the DAS system. Following this, the system was operated in three consecutive states: normal operation from 19:50 to 19:54, a full leakage condition from 19:54 to 19:57, and a return to normal status from 19:57 to 20:00. Finally, the water pump was deactivated between 20:00 and 20:03. During this stage, the DAS system focused on capturing transient hydraulic vibrations as the water flow transitioned from a dynamic state to a static state.

Table 1: Pipeline leakage simulation test conditions and event records

Date	Time	Events
2025/10/23	19:46-19:50	Tap on the water supply pipeline
	19:50-19:54	Circulating water flow, start heating
	19:54-19:57	Circulating water flow, leakage valve fully open
	19:57-20:00	Circulating water flow, leakage valve closed
	20:00-20:03	Turn off the water pump

4 RESULTS AND DISCUSSION

4.1 Spatiotemporal Vibration Analysis

To intuitively analyze the spatiotemporal evolution characteristics of vibration signals, this study calculated the RMS intensity of the signals. Figure 2 shows the RMS intensity waterfall plot of DAS signals throughout the third test, which clearly distinguishes transient disturbances such as knocking from persistent events such as leakage. Different events display significant characteristic differences in both spatial and temporal dimensions. Specifically, periodic strong signals were observed near Channel 36 between 19:46 and 19:50, which matches the transient and incidental nature of knocking events. After 19:50, continuous water circulation signals appear near the leakage point at Channel 29. Crucially, when the leakage valve was opened at 19:54, the signal intensity of Channels 29 and 30 immediately shows a persistent step increase. This waterfall plot intuitively confirms the distinguishability between persistent leakage and transient disturbances in the temporal dimension.

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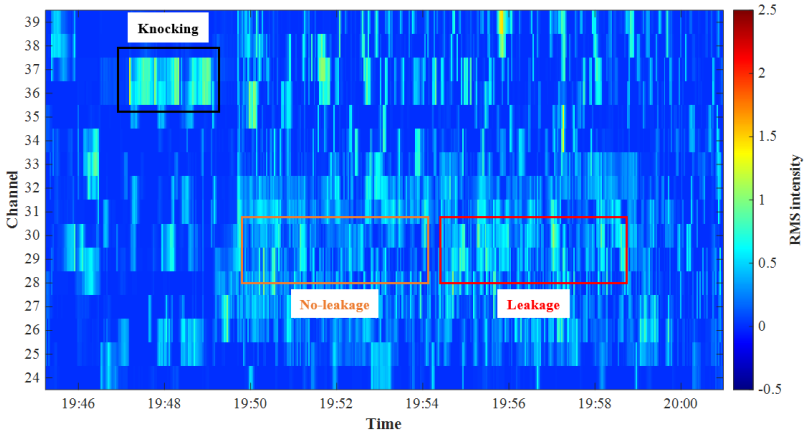


Figure 2: Schematic diagram of the pipeline model test system

4.2 Spectral Feature Identification and Spatial-Frequency Mapping

Although root-mean-square (RMS) analysis effectively captures the spatiotemporal energy evolution of signals at the macro level, it falls short in revealing the detailed spectral features hidden behind energy changes. To further explore the signal frequency components at the leakage point, this study carried out short-time Fourier transform (STFT) analysis on the data from Channel 29. Figure 3 compares the 2D time-frequency spectrograms of vibration signals before (a) and after (b) the leakage.

As shown in Figure 3(a), the background signal before leakage exhibited a low vibration amplitude, with its peak intensity generally below 0.015. Energy was mainly concentrated in the low-frequency band, with most of these frequencies falling below 800 Hz. This reflects the natural low-frequency characteristics of steady fluid flow in the pipeline. High-frequency components above 1 kHz were almost inactive, leaving the high-frequency region visually dominated by a dark blue background. In contrast, once the leakage valve was opened, the spectrogram underwent a significant transformation, as shown in Figure 3(b). A distinct broadband energy surge was observed. First, the vibration intensity increased sharply, with the peak amplitude exceeding 0.025. This magnitude is prominently indicated by the red regions in the heatmap, which verifies the step-like growth observed in the RMS analysis. More importantly, the signal bandwidth expanded greatly. The high-energy zone was no longer limited to the low-frequency band but extended to 1.4–1.5 kHz. The emergence of such high-frequency spectral components is a typical acoustic feature of high-pressure water jets.

This detailed spectral comparison proves that a leakage event not only elevates the overall energy level but also introduces specific high-frequency spectral features, fully demonstrating the ability of the DAS system to capture the fine acoustic characteristics of pipeline leakage. However, relying solely on the analysis of a single measuring point is insufficient. To ensure the robustness of detection, it is necessary to further investigate the spatial distribution of these spectral features, thereby confirming whether such high-frequency anomalies can be clearly distinguished from the background water flow noise monitored by other fiber-optic channels along the pipeline.

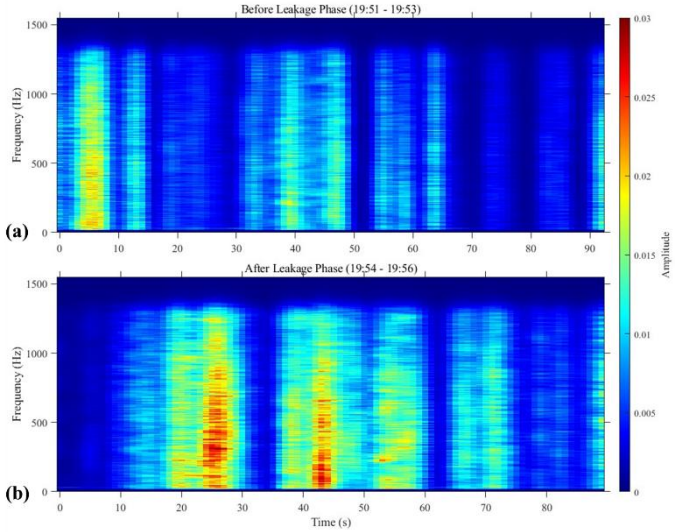


Figure 3: 3D time-frequency spectrogram of vibration signal (a) before leakage and (b) after leakage

The spatial distribution of spectral features was further examined using Power Spectral Density (PSD) analysis to ensure robust detection and localization. As illustrated in the 2D PSD difference heatmap (Figure 4), the energy variations between the leakage and non-leakage states are explicitly visualized. This differential approach effectively highlights a prominent energy concentration strictly localized at Channels 28 and 29, successfully separating the leakage-induced acoustic features from the background fluid noise. To precisely quantify these spectral anomalies, Figure 5 presents a smoothed PSD comparison for these two specific channels. Under normal operating conditions, the baseline fluctuations remain weak, with negligible energy distributed in the high-frequency band near 1.4 kHz. Conversely, during a leakage event, the spectral distribution undergoes a dramatic shift. The smoothed curves clearly demonstrate a high-intensity, broadband energy surge extending from several hundred hertz up to 1.4 kHz. This specific frequency expansion is a typical acoustic signature of high-pressure water jets. Ultimately, by isolating these unique high-frequency spectral features, this comparative analysis effectively filters out high-energy, low-frequency background interference, thereby ensuring accurate leakage positioning and reliable detection at Channels 28 and 29.

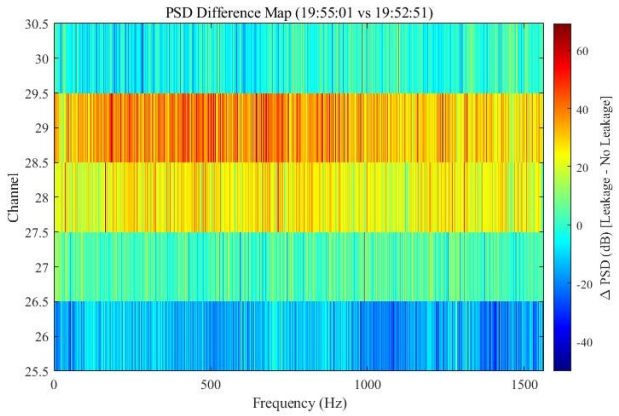


Figure 4: Heatmap of spatial-frequency energy variations (Δ PSD) between the leakage and non-leakage states

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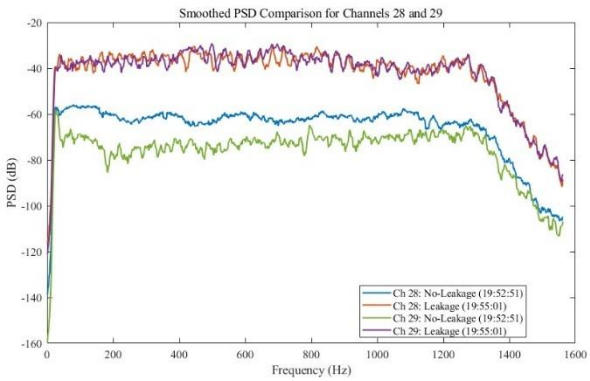


Figure 5: Smoothed PSD comparison curves for Channels 28 and 29

4.3 Thermal Verification and System Synergy

The leakage events were further corroborated from a thermal perspective using the Distributed Temperature Sensing (DTS) system, as illustrated in Figure 6. Before the leakage, the temperature profile along the optical fiber remained stable at a baseline ambient level of approximately 25 °C. Once the leakage started, pronounced thermal anomalies were recorded. The temperature elevation was most intense within a 1-meter radius of the leakage source, specifically between the 126.1 m and 127.1 m marks. The thermal response attenuated progressively as the distance from the leakage point increased, demonstrating high spatial sensitivity. These experimental results confirm that the DTS system can pinpoint the leakage location with a spatial precision of 1 m, providing critical accuracy for targeted maintenance in practical engineering applications.

Despite its spatial precision, a limitation in the temporal response of the DTS system was observed. The temperature rise manifested gradually rather than instantaneously. For instance, reaching a predefined detection threshold of 5 °C above the ambient temperature required approximately 14 minutes at the primary leakage point. This temporal delay is primarily attributed to the physical processes involved, namely the time required for the fluid to permeate the pipeline's insulation layer and the subsequent heat conduction to the sensing cable. Because of this inherent thermal lag, the integration of DAS and DTS technologies becomes indispensable. While the DAS system offers near-instantaneous, real-time alerts within seconds, it remains comparatively susceptible to environmental acoustic noise. Conversely, the DTS system provides a slower but highly reliable and interference-resistant verification of the event. The synergistic application of these two technologies effectively resolves the inherent trade-off between response speed and detection reliability, thereby establishing a robust and comprehensive monitoring framework for pipeline infrastructure.

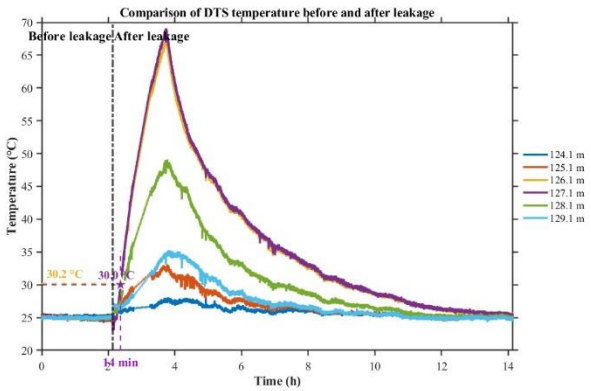


Figure 6: Comparison of DTS temperature before and after leakage

5 CONCLUSIONS

In this study, the integration of DAS and DTS is demonstrated as a robust and real-time monitoring solution for urban pipeline leakage detection. Based on the experimental results, the following conclusions are drawn:

(a) The implementation of DAS technology provides an immediate response to leakage events via vibration signals, with the vibration PSD observed to increase from -50 dB to -20 dB upon the occurrence of a leak. This sensitivity facilitates millisecond-level early warning and precise spatial localization through the identification of high-frequency spectral footprints.

(b) The thermal data obtained from DTS indicate that temperature changes associated with leakage are gradual rather than instantaneous, with a detection delay of approximately 14 minutes recorded in this investigation. However, DTS measurements are significantly less influenced by environmental noise compared to acoustic methods, allowing for the stable and reliable verification of leakage events.

(c) The synergistic application of DAS and DTS effectively resolves the technical trade-off between monitoring timeliness and detection accuracy. By combining the high-speed response of acoustic sensing with the high-confidence thermal field data, a comprehensive health diagnosis framework is established for the proactive safety management of underground infrastructure.

(d) To further enhance safety management, future work will integrate the proposed DAS-DTS framework with Internet of Things (IoT) sensors, such as Global Navigation Satellite System (GNSS) for three-dimensional displacement, tiltmeters for inclination, and soil moisture sensors. These will allow for a synergistic analysis of both structural deformations and subsurface leakage. This multi-parameter approach will facilitate earlier warning capabilities and a deeper understanding of pipeline failure mechanisms.

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